Enhancing navigation information with tactile output embedded into the steering wheel

Conference or Workshop Item

Enhancing Navigation Information with Tactile Output Embedded into the Steering Wheel

Dagmar Kern[1], Paul Marshall[2], Eva Hornecker[2,3], Yvonne Rogers[2], Albrecht Schmidt[1]

1: Pervasive Computing and User Interface Engineering Group, University of Duisburg-Essen, Germany
2: Pervasive Interaction Lab, Open University, Milton Keynes, UK
3: Dept. of CIS, University of Strathclyde, Glasgow, UK
dagmar.kern@uni-due.de, p.marshall@open.ac.uk, eva@ehornecker.de, y.rogers@open.ac.uk, albrecht.schmidt@uni-due.de

Navigation systems are in common use by drivers and typically present information using either audio or visual representations. However, there are many pressures on the driver's cognitive systems in a car and navigational systems can add to this complexity. In this paper, we present two studies which investigated how vibro-tactile representations of navigational information, might be presented to the driver via the steering wheel to ameliorate this problem. Our results show that adding tactile information to existing audio, or particularly visual representations, can improve both driving performance and experience.

1 Introduction

Humans are limited in what they can simultaneously perceive. This is particularly noticeable when driving a car and trying to do something else at the same time, such as talking and changing the radio channel. In-car navigation systems are now making new demands on a driver's attention [3]. Extensive research has been carried out to investigate how this cognitive demand might be reduced through the provision of various kinds of collision detection systems and on how best to warn the driver of possible collision using different modalities and also representing information in multiple modalities (see [13]). Our research focuses on a less safety-critical aspect of driving, although one that is still affected by the multiple stresses on a driver's attention: navigating when using an in-car navigation system.

In-car navigation systems are common and many drivers use them regularly. Typically, three types of systems are in use: (1) built-in systems offered by the manufacturer (2) specific navigation add-on devices offered by third party companies, and (3) navigation applications on mobile phones which include GPS. Sales trends show that these devices are increasingly being used and that it will be the norm to use a navigation system within the next few years[1]. In our work we are investigating how

1 http://www.telematicsresearch.com/PDFs/TRG_Press_Jan_08.pdf

vibro-tactile output, as an additional channel, can help to provide navigation information without interfering with the overall user experience and without distracting the driver.

From a technical perspective, the devices of built-in systems are more tightly integrated with the car's sensors, displays, and speaker system. The main navigation screen in these systems is often of high fidelity and commonly only shared with other information and entertainment systems in the car. Hence, when using one of the other functions (e.g. browsing the music collection or looking up weather or news) this screen is not used for navigation. In many built-in designs there is an additional display of smaller size (e.g. in the dashboard or the head-up-display) that shows only the next action for the driver. The audio output of built-in systems is linked to other audio sources in the car and, hence, it can be prioritized over entertainment content. However, if the user listens to the radio, to music or information, the interruption is disruptive and interferes with the user experience.

In contrast, add-on devices typically provide an additional single screen that can be exclusively used for the navigation task. The audio output is provided by additional speakers, but which compete with the in-car audio system for the user's attention. Some of these devices can be linked to the in-car audio system via Bluetooth for a tighter level of integration. Navigational applications on mobile phones are similar to add-on devices with regard to their output capabilities, with the exception that the output channels may be shared with other applications on the phone (e.g. SMS, music player, calling) and hence the output channel is not exclusive to the navigation application.

All of these systems provide visual and audio output to convey information about the recommended driving direction to the user. The complexity of the information presented varies from simple directional indicators (e.g. an arrow that indicates the driver should turn right or left at the next crossing) to complex 3D scenes (e.g. a first person view of the geographical surrounding with an added arrow indicating driving directions) and map views. The additional audio information can also vary in complexity, ranging from simple commands (e.g. "turn right") to longer explanations (e.g. "take the next exit and continue towards highway 7").

If visual and audio output are present and the user concentrates on the driving task then current systems work very well. However, this optimal scenario often fails to occur in real driving scenarios as drivers engage in many tasks while driving, ranging from social conversation with passengers, talking on the phone or consuming entertainment such as music or audio books. These additional tasks are important to the driver and contribute significantly to the user experience. For example, engaging in a conversation or listening to an audio book can keep the driver alert and may make a trip seem shorter. The audio output of current navigation systems fails to integrate well with these practices and hence can negatively affect the user experience.

Answers given by participants in our user studies indicated that audio output is problematic for many users of these navigation systems. They deal with this issue in different ways. A common approach is to mute the navigation system while in conversation or listening to the radio or music, and to rely exclusively on visual information. However, people reported that this can lead to missing turns as the audio doesn't prompt them to look at the display. In this situation, the driver either has to focus on the navigation system or risk missing important information.

These considerations, and previous work on tactile driver warning systems, e.g. [6] motivated us to look at different modalities for presenting navigation information to the driver. Our hypothesis was that vibro-tactile signals might be less intrusive than audio signals and interfere less with other activities. Our study therefore explores the design space of different modalities for presenting information to the driver. We created a prototype to explore the utility of vibro-tactile feedback in the steering wheel both for transmission of simple information and as an additional modality that supplements the conventional channels.

2 Prototype and Design Space

To build our prototype navigational system, we first assessed potential locations in which to present vibro-tactile output in terms of feasibility and user experience. To make vibro-tactile output useful as an additional modality a central requirement is that the actuators are in constant contact with the user. This leaves three potential options for integration: steering wheel, pedals and floor, and the driver seat.

We decided to explore the design space for the steering wheel. Some car manufactures have recently added vibration output to their steering wheels for warning signals e.g. Audi[2]. The whole steering wheel vibrates to provide binary information. There has also been initial work on providing tactile information in the steering wheel to communicate more specific information that inspired our prototype [4]. The seat has been used to provide coarse tactile information, e.g., for warnings[3] or other information [10, 14].

The steering wheel is used with hands and fingers, which are very sensitive to tactile information. Additionally, in contrast to the body (driver seat) or feet (pedals), fingers are usually bare, making it easier to provide rich tactile information. To explore the design space we created a prototype steering wheel with integrated tactile actuators. An advantage of integrating the signal into the steering wheel is that the signal itself might intuitively prompt the driver to turn the wheel using a direct physical mapping [8], nudging and tugging the driver in the correct direction. This approach has been successfully employed, for example with a shoulder-tapping system for visually impaired people [11] which was preferred over and engendered better performance than audio feedback. According to research on stimulus-response compatibility (see [9]) spatially corresponding mappings yield better performance than non-corresponding mappings, and matching modes of stimuli and response (e.g. manual responses to visuo-spatial stimuli). This further motivates investigation of vibro-tactile cues in the steering wheel.

The system consisted of a microcontroller (PIC 18F252), 6 power drivers, 6 vibration motors, and a Bluetooth communication module (Linkmatik). The microcontroller ran a small application that received commands from the serial line (via Bluetooth) and controlled the vibration motors using a pulse-width-modulation via power drivers. Via the Bluetooth module, the prototype can be connected to a test

2 http://www.audiworld.com/news/05/naias/aaqc/content5.shtml
3 http://www.citroen.com.hk/tech/sec_04.htm

application or the navigation system. Each vibration actuator could be controlled individually with regard to intensity and duration of tactile output. The minimal perceptible duration for the on-time of the motor is about 300ms and about 5 levels of intensity could be discriminated. Any software that can send command strings over the Bluetooth serial link could generate the control commands. In our experimental setup we used Flash and Java on a PC to control the hardware.

The physical design was a steering wheel the same size as that found in cars. The vibration motors (6 x 3.5 cm) were integrated on the outer rim of the wheel under a layer of rubber (see fig 1). It was attached on top of a gaming steering wheel used to control car racing games (logitec). This acted as controller for our simulated driving task.

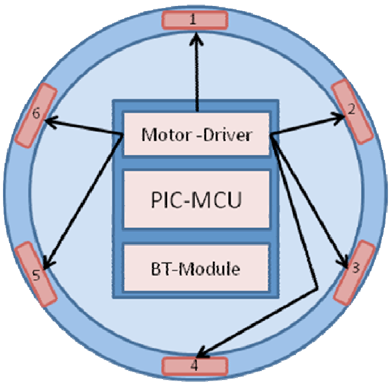

Figure 1: The steering wheel: concept and internal data flow and photo of the prototype used in the study with the elements exposed.

In the design of the tactile output we were able to use the following dimensions: 1) number of actuators: each of the six actuators could be used independently; 2) intensity: the intensity of each actuator could be controlled independently from an off-state up to level 5; and 3) timing of the signal: the actuators could receive signals at any time. This enabled us to create static output (e.g. switching on the left side of the steering wheel with a medium intensity for 2 seconds) as well as dynamic patterns (e.g. activating vibration in a circular pattern moving clockwise, with 1 actuator always on and a brief overlap during transitions).

For our comparative studies, we mainly focused on static patterns because our current setup with only six distinct locations (actuators) for the signal limited the fidelity of dynamic patterns and the speed of the traveling signal. Our static pattern consisted of two different vibration signals: 1) vibration on the right side (actuators 2 and 3 turned on) indicating that the driver should turn to the right; and 2) vibration on the left side (actuator 5 and 6 turned on) indicating a left turn.

However, we also used the study as an opportunity to probe the general feasibility of dynamic patterns. We introduced a dynamic circular pattern, where the vibration signal moves along the wheel (i.e. a vibration signal starts at actuator 1 with full intensity, then after 300ms the vibration stops and starts immediately at actuator 2 for the same time with the same intensity and so on). The idea is to lead the driver to turn the wheel in the correct direction by following the moving signal, i.e. when it moves from left to right the driver should turn to the right and vice versa. Dynamic patterns are also an interesting alternative, since they are not affected by extreme turns of the steering wheel and could transmit more complex information. Integrating many small actuators into the wheel would allow the signal to quickly move between adjacent actuators, enabling the user to, for example, feel the vibration move along the fingers of one hand.

In the studies described below we concentrate on simple static vibration signals. This was feasible because our test situation required no extreme turns. Thus, there was no risk of the wheel being turned around to a degree where a vibration on the left side of the wheel might be felt at the driver's right hand. Participants were instructed to keep both hands on the wheel. To ensure that they felt the vibration regardless of where their hands were located (the next motor might be a few centimeters away from the hand) the vibration signal had to be put on maximum intensity. This unfortunately resulted in some vibration transmitting to the entire wheel, negatively affecting the ease of distinguishing left/right vibration.

3 Setup and Experiments

We ran two studies using an almost identical technical setup to explore the design space. Variations were due to the studies being run in different locations and lessons learned from the first study. Both studies utilized the steering wheel prototype and vibration signal (see fig 2).

The first study compared three conditions: a spatially localized audio beep (provided via headphones), a tactile-only condition, and an audio+tactile condition. The second study investigated spoken audio instructions, visual instructions (arrows), and multimodal instructions (visual+audio, audio+tactile, visual+tactile). While the first study aimed at a comparison of signals of similar length and informational content, the second study was designed to closer emulate current navigation systems which employ spoken instructions.

For the simulated driving task we chose a deliberately simple road layout, inspired by the Lane Change Task layout [7]. Our road consisted of three straight lanes. The participants had to drive on the middle lane of the road and to change to the left or right lane whenever they received a corresponding instruction and then return to the middle lane again. They also had to keep to the speed limit indicated by the road signs they were passing. Order and timing of direction instructions were randomized.

The chosen road layout offered the opportunity to easily measure direction recognition and driving performance without the risk that the drivers might turn the steering wheel to an angle where the actuators were not at the left or the right side. Recommended speed limits alternated between 30 and 50 km/h at varying distances. Participants also had to carry out a distractor task. The setup is depicted in fig. 2.

Figure 2. Setup in the first study with the control panel on a laptop (left), setup in the second study with control panel on a 8" display (middle) and a close-up of the control panel with an direction arrow used in the second study (right).

3.1 Software and Equipment

Participants were seated on a chair in front of our prototype steering wheel. The logitec driving game pedals were located on the floor, taped to the ground, and augmented to provide some resistance to being pressed.

The physical setup can be seen in figure 2. A 42" display behind the steering wheel emulated the view through the front window, showing the road ahead. As a driving simulator we employed CARS[4] , run on a PC. The CARS software was adapted to send messages to the vibration actuators using UDP over a Bluetooth connection. In the first study we utilized a laptop located towards the side of the driver behind the steering wheel to show the speedometer on a control panel, (see fig 2 right). Due to the design of our wheel prototype (with electronics filling the inside of the wheel) the control panel could not be placed directly behind the wheel. In the second study we used an 8" display to show the control panel, this time including navigation instructions for the visual information conditions (see fig 2, middle and right).

The drivers were equipped with a headset that delivered audio information, distracter information and tasks (background music emulating a radio show in the first study and spoken questions in the second study) and additionally shielded off audible noise from the vibration actuators. In the first study a Sennheiser HD 280 pro 64 Ω was used, and in the second study a Philips headset.

3.2 Study 1: driving with audio, tactile or combined directional information

In the first study we utilized spatially localized audio (a beep) as the most direct equivalent to a vibration signal for the audio condition. The audio signal was given by a 140 ms beep following guideline 7 from Green [5] about the duration of signal

[4] https://www.pcuie.uni-due.de/projectwiki/index.php/CARS

bursts. In the vibration condition two actuators were activated for 300 ms on the left or right side of the wheel (much shorter signals are not noticeable). The third condition combined audio and vibration. 16 participants took part in this study, with the order of conditions counterbalanced.

As a distractor task participants heard music through their headphones made to resemble a radio station playing standard easy-listening pop music, and were instructed to tell the experimenter when they hear a specific jingle. All music tracks were about a minute long, and the jingle lasted three seconds.

To investigate the general viability of a dynamic vibration pattern for conveying directional information, we presented the participants with a final task after they had completed the three conditions. The actuators were turned on one after another to create a signal moving along the steering wheel either clockwise or anticlockwise. Holding the wheel without any driving task, participants had to recognize and tell the experimenter either verbally or using gestures in which direction the signal was moving. We researched two different conditions: in the first one the signal made one circle of the steering wheel, meaning that each actuator was turned on only once; in the second condition, the signal made two circles of the steering wheel. In each condition they were presented with 16 instances, half running clockwise and the other half anti-clockwise in random order.

Design

A within-subjects design was employed, with each subject performing the task in all conditions (in counterbalanced order). Participants were first introduced to the simulator and to the task. The three modalities of directional information were demonstrated: audio, tactile and combined audio+tactile). They were then given six minutes to drive the simulator in order to get used to it with signs on the road giving left-right instructions.

Each condition then lasted six minutes, during which subjects received 18 instructions (nine left and nine right) in random order. The time between instructions was randomly between 15 and 24 seconds. Subjects were instructed to drive in the middle lane and to switch to the left or right lane according to the signal and to come back to the middle lane immediately after having reached the respective lane. At the end, participants were given a questionnaire and asked to rate the conditions according to their preferences (e.g. being annoying or pleasant). Further open-text explanations (e.g. why it was annoying) for their statements were collected, as well as demographic data.

As dependent variables we assessed driving performance, measured in terms of lane keeping (mean deviation from the race line) and compliance to the suggested speed and correctness of lane-shifts in both studies.

As a measure of lane keeping we examined the position of the car on the street in comparison with an ideal race line that we assume participants should drive along (cf. [7]). Every 20 millisecond the standard deviation of the mean distance of the car from the ideal race line was calculated up to this point. To make the calculation of the curves to the left and right lane easier we approximate them also with straight lines, see figure 3.

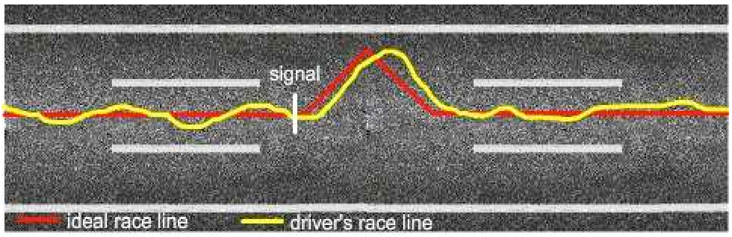

Figure 3 graphical representation of calculating the driving performance by measuring the standard deviation of the mean distance to the ideal race lane.

Participants

16 participants took part in the study: 9 female and 7 male, aged 25 to 52 (mean of 36). All were administrative or research staff from the Open University. Driving experience varied from having held a driving license from 1 year up to 36 years (mean of 15.3 years) . Only 2 people had less than 6 years driving experience. The majority (nine people) drove more than five times per week and only five drove less than once a week. Only one used a navigation system, but reported that they frequently turned off the audio when listening to radio or talking with other passengers.

3.3 Results of user study 1

Analysis of driving performance data

The effects of representing directional information in different modalities (audio, tactile or audio+tactile) were compared for three measures of driving performance using repeated-measures ANOVAs: likelihood of moving in the correct direction, average speed and mean standard deviation from the race line.

There was an effect of interface condition on participants' accuracy in choosing whether to steer left or right, $F(2, 28) = 14.25$, $p < .001$. Planned comparisons showed that participants were correct less often in the vibration condition ($M = 16.4$) than in either the audio ($M = 17.9$), $p < .01$, or combined condition ($M = 17.9$), $p < .005$. There was no significant difference in accuracy between the audio and combined conditions, $p > .05$. There was no significant effect of the modality of directional information on the average driving speed, $F(2, 30) = 2.42$, $p > .05$. There was also no effect of the modality of directional information on the standard deviation from the race line, $F(2, 30) = 1.04$, $p > .05$.

Therefore, we can conclude that the tactile information led to decreased driving performance compared to the audio and there was no improvement in providing both together. There were however interesting qualitative responses to the different modalities from participants' responses to the questionnaire. These are outlined in the next section.

All participants were able to distinguish the direction of the dynamic vibration signal in the follow-up experiment. The variation of having the signal run twice around the wheel was preferred, as this enabled a confirmation of the initial judgement after the first round. The fidelity of the signal (due to our setup with only six actuators) was not high enough to be easily detected.

Analysis of questionnaire results

The questionnaire asked participants to rate the output modality variation they preferred and to what extent they found each pleasant, annoying or distracting. There was no significant effect of interface condition on the rating of pleasantness, annoyance or distraction. However, 11 participants were found to prefer the audio-only interface and 5 preferred the combined interface. No participant preferred the vibration interface. A Friedman's ANOVA found differences in participants' preferences for different navigational systems to be statistically significant $\chi^2 = 11.37$, $p < .005$. Post hoc Wilcoxon tests indicated that the audio condition was preferred to the combined condition ($p<.05$), which was in turn preferred to the tactile condition ($p<.05$).

All of the participants in the first study gave extensive answers to the free text questions in the questionnaire. These asked them to explain what they liked and disliked, and what was annoying, pleasant or distracting in the three conditions as well as what they thought were advantages or disadvantages. These open text answers as well as remarks by participants during the study indicate that the preference for the audio condition was mostly due to difficulties in distinguishing the direction of the signal and the limitations of our prototype: for example, ensuring that vibration could be felt regardless of how or where participants held the wheel required a maximum intensity signal, which resulted in vibration transmitting across the entire wheel).

Almost two-thirds of the participants mentioned difficulties in distinguishing direction and location of the tactile vibration signal, possibly due to the insufficiencies of our current hardware implementation. Vibration on its own was considered to be less clear or comprehensible than the audio signal. Several participants thought there was a risk of confusing the signal with road vibrations or it being masked. As a practical issue, several participants mentioned that it might be hard to notice if only one hand is on the wheel (although this issue might be alleviated by a more sophisticated setup with many actuators). One possibility is that integrating more actuators into the steering wheel, increasing signal fidelity and reducing its intensity for a more localized signal, would provide a remedy to most of these issues except for the potential interference of road vibration.

Many general problems were listed for the audio-only condition, confirming our hypothesis that alternative modalities would be useful. Half of the subjects mentioned that background noise, conversation and radio could interfere, mask the signal or distract the driver. As a practical issue, hearing impairments were mentioned. The utility of spatially localized sound instead of verbal instructions was questioned, e.g. the audio signal could be masked by other sounds (although it should be noted that the beep signal was used more for reasons of experimental parity than practical utility). Participants furthermore wondered whether it would be feasible without headphones, as they would not want to wear headphones while driving, and were concerned that turning one's head around could lead to a mismapping of directions. Several participants commented on the audio being annoying. Thus, it seems that verbal instructions are superior to more abstract sound, even if they might feel tedious to listen to.

Overall, problems in one condition mirrored advantages of the other: Several people who mentioned background noise/radio as a problem for audio signals listed as an advantage of vibration that it would not be masked by surrounding noise, while the audio signal was listed by the majority as being "easier to notice" and to "distinguish direction".

Participants almost unanimously liked the multimodality of the audio+tactile condition. Its main advantage was seen in providing confirmation and reinforcement of the signal perceived in the other modality, and a backup in case one signal was missed, for example: "alerting more than one sense not to miss it"; "the sound reinforced the vibration"; and "the sound will confirm the vibration if the driver was not sure". A few people were concerned that an inconsistency in the combined signal would be highly confusing and that the combination of two modalities might become overwhelming or distracting when experienced over an extended time.

The questionnaire results led us to continue to explore the design space and to focus on the utility of vibration as auxiliary information. Results and user feedback indicated that this might be a likely avenue for finding benefits. That performance measures for speed and race-line for the vibration-only signal were comparable to the other conditions despite of the limitations of our prototype was encouraging. User feedback confirmed our hypothesis that audio information on its own is felt to be problematic in driving practice due to interference with the radio and passenger chat). Vibration-only might be useful, but needs much better prototypes (better resolution of signal) to be evaluated fairly. Further research in this direction will need to keep in mind users' concerns about one-handed driving and the possibility of road vibrations masking the signal.

3.4 Study 2: A comparison of different forms of multimodal directional information

The questionnaires in the first study revealed a range of concerns regarding spatialized audio (use of headphones while driving, danger of confusing directions when turning head during the audio signal). Furthermore a spatially localized beep sound is too restricted in terms of the information it can convey to be useful for complex driving instructions. The second study therefore investigated a more realistic scenario emulating existing navigation systems. This study investigated whether multimodal information improves performance and whether an auxiliary vibrotactile signal would outperform the existing combination of audio and visual information.

Design

A within-subjects design was again employed: participants took part in 5 conditions in counterbalanced order: audio information alone, visual alone, audio+visual, visual+tactile and audio+tactile.

Information was presented via spoken audio instructions (“please change to the left/right lane”) by a female computer voice, and in the visual conditions through an arrow next to the speedometer indicating the direction. The vibration signal, again, was given for 300 ms by two actuators on the left or right side of the wheel.

An audio distractor task was designed to emulate distractions from passenger conversations that interfere with audio navigation information. It consisted of mathematical questions, asking participants to calculate (e.g. “Peter and Paul are 16 together, Paul is nine, how old is Peter?”), with a ten second interval between questions. The volume of questions was lower then the audio instructions. Participants also had to pay attention to visual information by looking out for signs indicating the speed limit and making sure they did not go to fast or slow. All other aspects of the design were identical to the first study.

Participants

17 master’s students from the University of Duisburg-Essen participated in the second study: 2 female and 15 male, aged between 23 and 35 (mean 26). Driving experience varied from having held a license for between one and 12 years (mean of 7.8) years. 6 typically drove less than once a week, another 6 between one and four times a week and 5 five to seven times. Half (9 people) used a navigation system. Six reported that they found voice output inappropriate or disturbing when talking with passengers or listening to the radio. One reported turning it off while talking to people and another when listening to the radio. Three never turned it off. Those participants who used a navigation system were asked to specify on a scale from 0 (very often) to 5 (never) how often they miss turns while the voice output is turned off: the mean was 2.96 (standard deviation 0.94).

3.5 Results from user study 2

Analysis of driving performance data

Participants’ driving performance with each of the five representations of directional information (audio, visual, visual+audio, audio+tactile, visual+tactile) were compared using repeated-measures ANOVAs. Modality of the information had no effect on the number of correct lane changes $F(1.9, 30.3) = 2.45$, $p>.05$. There was also no effect of the modality on the average speed, $F(1, 16) = 1.21$, $p > .05$. However, there was a significant effect of information modality on the standard deviation from the race line, $F(4, 64) = 3.40$, $p < .05$. Mean standard deviations from the race line are shown for each condition in fig. 4.

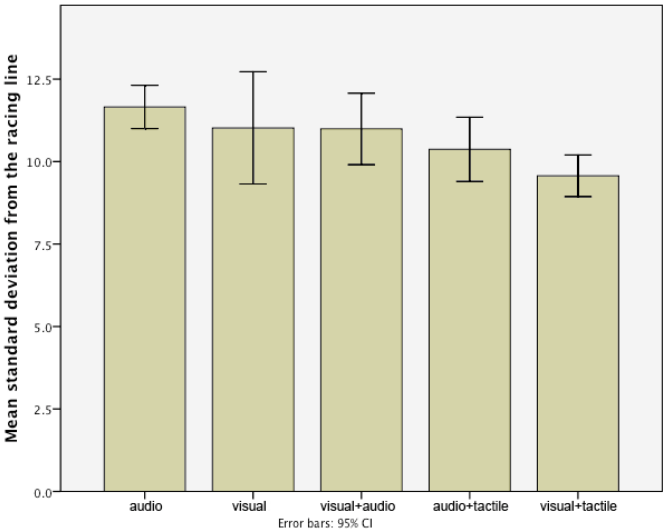

Figure 4: Mean standard deviation from the race line by condition. The combined tactile and visual condition has the lowest mean standard deviation.

Pairwise comparisons revealed that there was a significant improvement in performance when coupling audio with tactile information compared to audio alone ($p < .05$); however, there was no improvement when coupling audio with visual information compared to audio alone ($p > .05$). There was also an improvement in coupling visual and tactile information over visual information alone ($p < .05$), but no improvement over visual alone when coupled with audio ($p > .05$). There was no significant difference in performance between the audio+tactile and visual+tactile conditions ($p > .05$).

Questionnaire Data: Preference ratings

Participants were asked to rate each of the five navigational system configurations in terms of preference from 1 (most preferred) to 5 (least preferred). Preference scores were compared using Friedman's ANOVA. A significant effect of the type of navigational system was found on participants' preferences ($\chi^2(4) = 43.77$, $p < .001$). Wilcoxon tests were carried out to follow up on this finding. A Bonferroni correction was applied, so all effects are reported at a $p<.007$ level of significance. Both the visual+tactile (Mdn = 1, T = 3.71, p=.001) and visual+audio (Mdn = 3, T=2.81, p=.005) configurations were preferred to the visual alone (Mdn = 5). Similarly both the audio+tactile (Mdn = 3, T =2.76, p=.006) and visual+audio (T=3.10, p=.002) configurations were preferred to the audio alone. The visual+tactile configuration was also preferred to the other two multi-modal configurations: visual+audio (T= 3.70, p=.001) and audio+tactile (T=3.25, p=.001). There was no significant difference in preference for the audio+tactile and visual+audio configurations. Therefore to summarize, multi-modal are preferred to single modal navigational system and the most preferred multi-modal configuration uses visual and tactile representations.

Questionnaire Data: Ratings of Pleasantness and Annoyance

Participants were asked to score how pleasant and annoying each of the navigation systems were to use, indicating their preference by crossing a line. The distance along the line was then measured and translated into a scale ranging from 0 (not at all) to 5 (very). Mean ratings are shown in figure 5 for both pleasantness and annoyance.

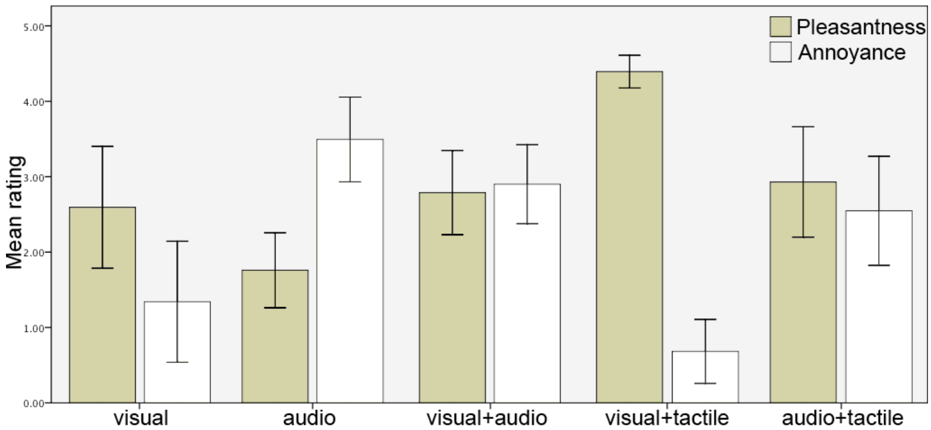

Figure 5: Mean rating of how pleasant and annoying the conditions were perceived to be (0 = very unpleasant, 5 = very pleasant).

Mauchly’s test indicated that the assumption of sphericity had been violated for the pleasantness scores ($\chi^2(9) = 27.6$, $p<.05$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.49$). A significant effect of navigational system was found on pleasantness ratings, $F(2.0, 31.4) = 12.3$, $p<.001$. Planned contrasts revealed that visual+tactile was found to be more pleasant than visual alone ($p<.001$), visual+audio ($p<.001$) and audio+tactile ($p<.005$). No significant differences were found between the audio and visual+audio ($p>.05$) or audio+tactile ($p>.05$).

Mauchly’s test also indicated that sphericity had been violated for the annoyance ratings ($\chi^2(9) = 31.7$, $p<.05$)), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.54$). A significant effect of navigational system was again found, $F(2.2, 34.6) = 16.7$, $p<.001$). Planned contrasts revealed that participants found no difference between visual+tactile and visual alone in terms of how annoying they were ($p>.05$), but found the visual+audio to be significantly more annoying than either visual-alone ($p<.005$) or visual+tactile ($p<.001$). Adding vibration ($p<.01$) or visual representations ($p<.05$) to audio were found to make it significantly less annoying. Audio+tactile was found to be significantly more annoying than visual+tactile ($p<.001$).

In summary, participants tended to find the visual+tactile representations both most pleasant and least annoying. The audio navigational system was found to be particularly annoying and unpleasant. This effect was ameliorated somewhat by combining it with another representation: either tactile or visual.

Questionnaire Data: Ratings of distraction

Participants were also asked to rate how distracting they found each of the navigational systems, again by crossing a line between the extremes of 'very' and 'not at all'. Mean ratings of distraction are represented in figure 6.

Mauchly's test indicated that the assumption of sphericity had been violated for the distraction ratings ($\chi^2(9) = 19.3$, $p<.05$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.58$). A significant effect of navigational system was uncovered, $F(2.3, 37.0) = 4.8$, $p<.05$. Planned contrasts revealed that participants perceived the visual alone system to be more distracting than the visual+tactile ($p<.001$), but no more distracting than the visual+audio system ($p>.05$). The audio system was perceived to be neither more nor less distracting than the audio+tactile system ($p>.05$), or the visual+audio system ($p>.05$) The visual+tactile system was perceived to be less distracting ($p<.05$) than the visual+audio system.

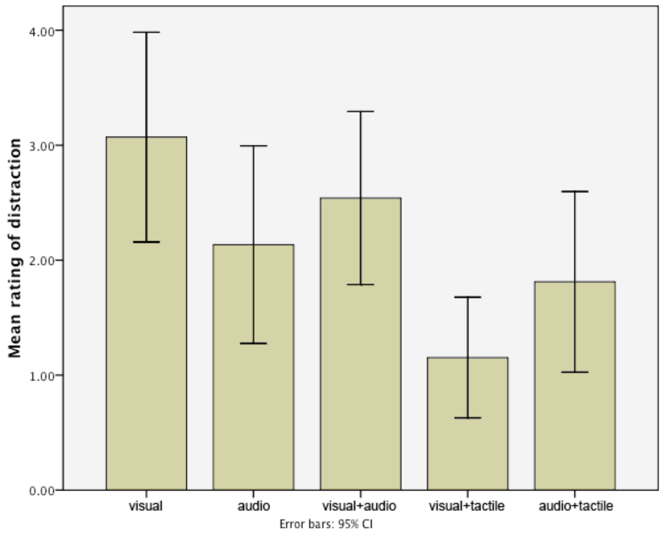

Figure 6: Mean rating of perceived distraction (5=most, 0=least distraction). The visual-only and the visual+audio condition are considered most distracting.

Questionnaire Data: Summary

The navigational system that combined visual and tactile information came out as a clear winner in participants' questionnaire responses. In the preference ratings, it was preferred to all other modality variations. Multi-modal systems were also preferred generally to the single modality systems. The visual+tactile system was found to be the most pleasant system to use, the least annoying and the least distracting.

The most frequently listed advantage for the audio condition was that audio information allows the driver to keep their eyes on the road (7 times) and that it is very salient (4 times). As a disadvantage, interference with conversation was listed, and that it can quickly become annoying. Participants seemed to perceive as an advantage of the visual information display that it does not distract from driving or listening to passengers. Four people mentioned that its biggest advantage is that one can look a second time and therefore do not need to remember the information. Visual information was considered useful as a back-up and confirmation for another signal that has not been well understood or clearly perceived, in particular since it does not disappear and can be looked up again. The back-up/confirmation function was listed frequently for all of the multimodal conditions.

The biggest disadvantages of visual information, listed most often, are that it requires the driver to look away from the road (listed 10 times) and can be missed as it does not attract attention unless glancing at the display. An auxiliary channel, either audio or vibration, was felt to provide a remedy to both disadvantages. Few people listed any disadvantages for the visual+tactile condition, while visual+audio was listed by a some people as having the 'disadvantages of both'. Vibration was valued as more ambient and less distracting by a few people and also listed as being fast and providing the least distraction from traffic or conversation.

3.6 Limitations and potential improvements

The studies were conducted in a simulator setting and not in a car, hence there were no vibrations induced from the actual driving. In current cars there are suspension mechanism that ensure that little vibration from the road can be felt in the car and in particular on the steering wheel. We expect that the results acquired with the simulation environment are similar to those in an actual car.

Due to our prototype hardware setup we have tested the general viability of using vibration signals using a fairly rough-grained signal (only 6 actuators and switching times of 300ms). Participants were able to identify the information from static (left side or right side vibrates) signals well, leading to increased performance. They were furthermore able to distinguish a dynamic pattern of the vibration moving directionally around the wheel (left to right or right to left). However the small number of actuators and the long switching time of our prototype consequently made the pattern too 'slow' to be utilized during a driving task. Even with these limitations of using a static signal (instead of a dynamic pattern) we achieve a better user experience. We expect that with more actuators distributed throughout the steering wheel and a faster-moving signal, the experience could be further improved with vibration being felt to move between the fingers of one hand on the wheel, supporting one-handed driving.

4 Discussion and Conclusions

Presenting information to users during a driving task is challenging. The central goal is to communicate useful information in a timely fashion without creating distraction and without increasing the cognitive load. Navigation devices provide just-in-time information for drivers on upcoming decisions, such as turning at the next corner or changing lanes. Providing this information in small pieces at the time the driver needs it to decide where to go eases the navigation task and hence reduces cognitive load and distraction. However, how this information is provided remains crucial as it is typically presented to the driver in situations where the primary task requires additional caution (e.g. taking a turn or driving off a motorway). The modality in which this information is represented can be critical, especially given the limitations to what the human cognitive system is able to simultaneously perceive. There are multiple potential demands on a driver's attention: talking with passengers, telephone conversations, looking out for potential dangers and in the car's mirrors, to name just a few.

In the research described in this paper we investigated the effects of presenting vibro-tactile information to the driver [6, 14]. In particular, we looked at the effect of presenting navigational cues with vibration output embedded into the steering wheel. Our hypothesis was that as most driver distractions are either visual or auditory, by presenting tactile information, we might minimize the cognitive load associated with navigation. The result of the first study indicated that vibro-tactile information display may not be as beneficial as more conventional auditory display of information in a distracting environment. This was because participants found it more difficult to perceive the direction represented by the tactile information and thus made more directional mistakes. Largely because of this, the participants preferred an auditory interface. We predict that tactile output in our prototype could be improved upon to increase the perceptibility of information (e.g. by using tactons [1]). However, based upon our user feedback, we chose to pursue the different approach of investigating whether representing redundant information in the tactile modality might be beneficial and favoured over single modality setups. In the second study we investigated whether multimodal representation of directional information would be associated with improved driving performance compared to single modality visual and audio representations. We also compared users' qualitative impressions of the different systems using questionnaires.

As predicted, we found the best driving performance in the conditions where there was redundant multi-modal representation of information. However, this performance improvement was only found in the two conditions where audio and visual representations were coupled with vibro-tactile representation and not where visual and audio representations were combined. As the task carried out by the participants was highly demanding of visual and auditory attention, one plausible explanation for this finding is that the participants were able to use the tactile information as a pointer to tell them when to attend to the other forms of information being presented, thus enabling them to offload the cognitive work associated with monitoring for navigational information in the auditory or visual modalities and allowing them to concentrate on the driving and auditory distracter tasks (cf. [12]). Some participants indicated in the questionnaire that they relied primarily on the tactile representation for navigational information, but were able to use visual or auditory information as a backup where they were unsure which direction had been indicated.

This finding is supported and augmented by the questionnaire findings: participants showed a strong preference for the multimodal navigational interfaces, and in particular visual information coupled with tactile information. Participants reported finding audio information on it's own distracting when they were trying to concentrate on speech. This led to an unpleasant experience and annoyance, which was somewhat ameliorated through the simultaneous provision of tactile information.

Our research suggests that the current design of in-car navigational systems, where both visual and audio output are combined, is acceptable for users, but inferior to the combination of visual output and embedded vibration suggested in our work. Our observations suggest that users rely on the vibro-tactile output as a trigger and use the visual display for confirmation and to gain additional information. The main advantage over audio as second modality is that vibration is unobtrusive, does not hinder ongoing conversation, and does not interfere with music or media consumption.

Overall the design recommendation drawn from the results are to present navigational information multimodality combining visual and tactile output. Our results, found that despite using a quite crude form of tactile interface, such a design improves the driving experience and might make it saver.

In further work we will investigate further how vibro-tactile presentation influences driving performance and overall user experience. In particular we are interested what effects spatial distribution, fidelity of tactile output, and timing of the actuators have. A potential way of increasing the fidelity of tactile information might be to use tactile icons or 'tactons' [1,2], where directional information might be associated with a particular tactile pattern.

We also plan to use more sophisticated measures to quantify changes in visual attention when tactile feedback is introduced, using an eyetracker. Here we expect that the driver will look significantly more at the road. Our current hardware includes an acceleration sensor that provides information about the steering angle; in a car similar information could be obtained from the can-bus. Making use of the measured angle of the wheel we plan to compare the effect of output that is relative to the wheel or relative to the car. This is important when the information is presented while the wheel is turned far out of its normal position, e.g. while turning. In the first case output on the left side would always be on the same (originally left) part of the wheel (which may then be on top if turning right) and in the second case output on the left will be always on the left side of the car. From a technical and systems perspective we are currently improving the output actuators (allowing faster switching and greater spatial resolution) and looking at options how to integrate this in an actual car – as built-in solution as well as an add-on device.

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